Impact of potential climate change on plant available soil water and percolation in the Upper Danube basin

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Abstract The soil root zone of the land surface provides plants with water for transpiration and therefore biomass production and its excess water percolates downwards and ultimately recharges the groundwater aquifers. Within the project GLOWA-Danube regional scale impacts of climate change on the water cycle are investigated. Potential changes in the water cycle based on climate scenarios for 2011 to 2060 are simulated with the decision support system DANUBIA that integrates models of natural as well as social sciences. This article presents the results of DANUBIA driven by an ensemble of 12 climates scenarios generated with a stochastic climate simulator regarding the future state of soil moisture and groundwater recharge in the Upper Danube basin.

Keywords soil moisture; recharge; climate change; GLOWA Danube; scenarios

INTRODUCTION

One of the most important water reservoirs at the land surface is the soil root zone. It provides plants with water for transpiration and therefore biomass production, and its excess water percolates downwards and ultimately recharges the ground water aquifers. Regional changes in precipitation and temperature patterns will thus change the availability of soil moisture for evapotranspiration and ground water recharge. Consequently, one aim of the Global Change research project GLOWA-Danube is to investigate the impact of regional Climate Change on soil water availability and the amount of percolation under different scenarios of future Climate Change. To simulate the hydrological cycle and the availability and use of water resources in agriculture, industry and households, the network-based, distributed decision support system DANUBIA (Ludwig *et al.*, 2003) was developed and is applied on the 77,000 km^2 Upper Danube river basin. Its framework allows for the integration of models from both, natural and socio-economical sciences which exchange data via common, well-defined interfaces (Barthel *et al.*, 2008). Therefore, DANUBIA is able to provide spatially explicit projections about future water availability and use based on a broad and plausible set of regional climate and socio-economic change scenarios for the period from 2011 to 2060. These projections of possible future change in the water cycle are discussed with key stakeholders to develop strategies to optimize adaptation measures to the regional impacts of Global Change.

The following analysis of potential changes in soil moisture and groundwater recharge is based on a thorough validation of the regional scale simulations with the DANUBIA land surface model PROMET in the Upper Danube catchment (Mauser & Bach, 2009). An ensemble of 12 different outputs of a stochastic climate simulator based on the IPCC-SRES-A1B emission scenario is taken as meteorological drivers to cover a plausible range of uncertainties in future regional climate development. Although constant land cover is assumed, DANUBIA's dynamic plant growth model reacts on changes in meteorological drivers and considers the impact of increased CO$_2$ levels on transpiration. The results of this model setup show a consistent picture of likely changes in plant water availability and recharge especially during the summer months.

Study Area

The Upper Danube basin is the study area investigated in GLOWA-Danube with a catchment area of about 77,000 km², covering large parts of southern Germany and the Austrian Alps. The heterogeneous catchment is characterised by strong meteorological (mean annual temperature: -4.7 °C to +9 °C, mean annual precipitation: 650 mm to >2000 mm) and altitudinal (287 to 4049 m a.s.l.) gradients (Ludwig *et al.*, 2003). The main land cover classes in the catchment are forest (40%) and grassland (27%), followed by arable land (23%). The soils in the central part of the catchment mainly are of silt loam and sandy loam texture, whereas the soils of the northern and southern, more mountainous parts are less developed with soil textures ranging from clay to sand depending on the weathering products of the underlying bedrock.

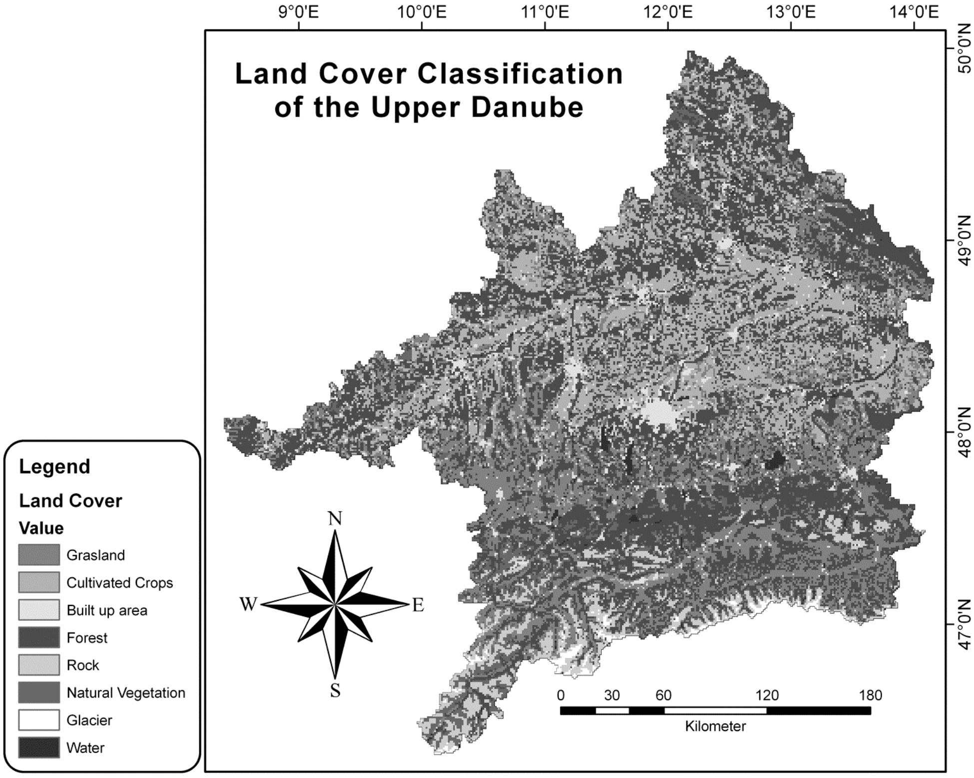

Fig. 1 Simplified land cover map of the Upper Danube catchment.

METHODS

This analysis of future trends in soil moisture and percolation with regard to Climate Change is based on simulations with the distributed hydrological model PROMET (Mauser & Bach, 2009) that computes the water and energy fluxes of the land surface within the DANUBIA framework. It is driven by a set of climate scenarios generated with the stochastic climate simulator developed within the scope of the GLOWA-Danube project (Mauser *et al.*, 2006). The different water flows at the land surface are computed with a time step of 1h and a horizontal resolution of 1km. To separate the Climate Change effect from other (anthropogenic) changes, static land cover based on CORINE 2000 (CLC, 2000) is assumed during the whole simulation period and plant cultivation is carried out within the temporal boundaries of past conditions. To account for the effect of CO_2 enrichment on plant development, the dynamic, biophysical vegetation module of Hank (2008) is used, which calculates transpiration, biomass production and energy balance of the canopy based on Farquhar *et al.* (1980).

The Soil Water Module

To simulate water fluxes in the soil column, PROMET uses a modified version of the Eagleson (1978) soil moisture model (Mauser & Schädlich, 1997) that predicts infiltration and exfiltration of the soil column. In recent years the model was extended for a soil layer stack with up to 4 layers and integrated in the decision support system DANUBIA along with other new modules of PROMET (Mauser & Bach, 2009). The soil water algorithm basically distinguishes between “wet” and “dry” time steps. Water sources for a soil layer can be infiltration from above (effective precipitation or percolation from upper soil layer) and capillary rise from the groundwater table or the lower soil layer. Water sinks on the other hand can be evaporation (top layer), root water uptake (all layers with roots) and gravitational drain (which is summed up with capillary rise for the net percolation of a soil layer). Actual infiltration is handled by Philip’s equation; excess water is added to the overland flow. If the net percolation of a soil layer exceeds the infiltration capacity of the soil layer below, the remaining water is added to the model output “interflow” (Fig. 2). All computations in the soil layer stack are run “top down”, which means that the most active upper layer is run first and the lowest, the least dynamic layer is run last. The spatial distribution of soil properties for the model runs is derived from the 1:1,000,000 soil map of Germany (BGR, 1998) and the soil hydraulic parameterisation is based on the works of Rawls & Brakensiek (1985) and Wösten *et al.* (1999). For more information on the recent setup of the soil model, the reader is referred to Muerth (2008). The ability of the model to reproduce soil moisture dynamics is shown for example in Loew *et al.* (2007) and Pauwels *et al.* (2007).

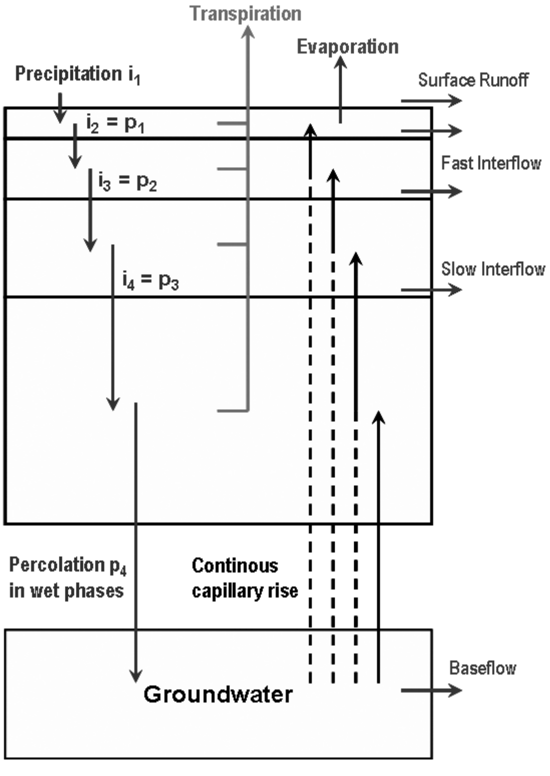

Fig. 2 Soil water fluxes as simulated by the modified 4-layer Eagleson model (from Muerth, 2008).

The Climate Scenarios

Four different future regional climate trends have been defined in the context of GLOWA-Danube, to investigate the potential impacts of climate change on the Upper Danube watershed (Mauser *et al.*, 2009). As the basis for all regional climate scenarios used as input data for DANUBIA, GLOWA-Danube assumes the IPCC-SRES-A1B (IPCC, 2007) emissions scenario prescribing the possible change of greenhouse gas emissions and the transformation of this emissions scenario into global climate trends through global climate models. The transformation of these global scale results into regional climate trends for the Upper Danube follow different approaches, but each trend provides the core information of the ascent in temperature in °C and the changes in precipitation in % for each half-year or season. Within this study, three of the four climate trends have been used, because they represent the range of possible changes in soil water availability during the scenario period 2011 to 2060.

The *IPCC regional* climate trend is based on the results presented in the IPCC report (2007) for Central Europe derived from 21 global climate models. The *REMO regional* trend is based on the application of the regional climate model REMO on Germany driven by ECHAM5 (Jacob *et al.*, 2008). The analysis of precipitation and temperature trends in historic (1960 to 2006) climate stations data of the German and Austrian weather services by Reiter *et al.* (in preparation) is the background of the *Extrapolation* climate trend. Because the historic air temperature increase of 1.65 °C in the Upper Danube region since 1960 is significantly higher than the global average trend of 0.65 °C +/- 0.15°C (IPCC, 2007), the projected acceleration of climate change in the A1B scenario leads to an increase in air temperature of up to 5.2 °C until the end of the century in our scenarios. This increase in temperature has the consequence of less precipitation in summer in most models and could increase precipitation in winter (as in the *Extrapolation* of past trends). The main characteristics of the GLOWA-Danube climate trends used in this study are depicted in Tab. 1.

While the general trend information is derived from climate model outputs, the actual meteorological time series used to drive the simulations at the 1x1 km^2 scale are the result of a stochastic weather generator (cf. Mauser *et al.*, 2006; Mauser & Muerth, 2008). This shuffling of recorded weather data according to predefined trends allows for the simulation of a Climate Change signal without the biases and uncertainties of using direct climate model output (e.g. Wood *et al.*, 2004). The weather generator re-assembles a scenario data set from weekly historical time segments of measured data based on the predefined trends of air temperature and precipitation. To cover a range of possible scenarios for each trend, multiple realisations were generated and four scenarios for each trend have been selected based on statistical criteria.

Table 1: Temperature and precipitation changes between 1990 and 2100 of the climate trends used in this study.

Scenario	Temperature increase (°C)	Change of precipitation (%) winter	 summer	Trend base
IPCC regional	3.3	+7	-14	IPCC (2007)
REMO regional	5.1	-4.9	-31.4	Jacob et al. (2008)
Extrapolation	5.2	+47	-69	Extrapolation of station data

RESULTS

The impact of the potential changes in the temporal distribution and the amount of precipitation on root zone soil moisture in conjunction with an increase in air temperature is of great interest to agricultural and forestry planning. The change in climate together with the adaptation of plant development and cultivation to this change also leads to an alteration of the water fluxes at the land surface, especially the recharge of groundwater. Because the recharge of groundwater at the regional scale is a complex problem due to unknown pathways in the deeper partially unsaturated zone, the following analysis concentrates on the vertical percolation of water from the soil root zone to deeper layers (see Fig 2). Averaged over the whole Upper Danube watershed, the annual amount of this vertical water flux is quite variable, as shown in Fig. 3 for the reference period. The course of future percolation in Fig. 3 is less variable, because the average of the four scenario runs of each climate trend are presented. During the reference period the model computes a slightly positive trend, whereas in the scenario period percolation decreases in all scenario runs. While the average annual percolation sum during the reference period (1971 to 2000) is 554 mm, the mean annual percolation during the second half of the scenario period (2036 to 2060) differs by -41 mm in the *IPCC regional* scenarios, by -62 mm in the *REMO regional* scenarios and by -76 mm in the *Extrapolation* scenarios. Overall, the range of changes in the regional climate presented here could lead to a reduction in average annual percolation by 7-14% over the next 50 years.

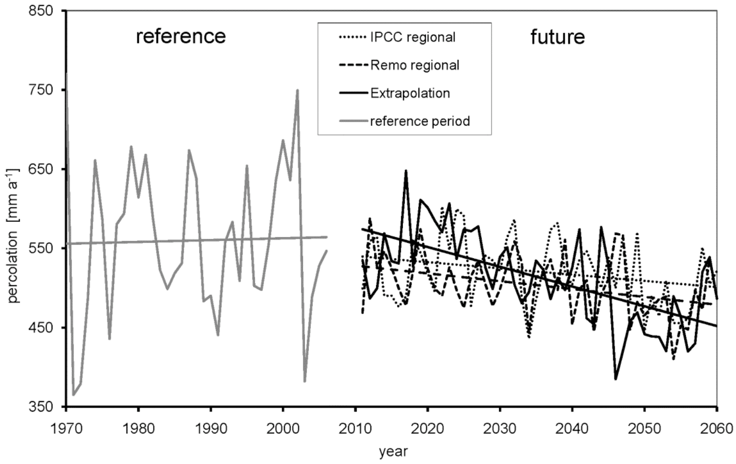

Fig. 3 Annual amount of percolation computed for the reference period (1971 – 2000) and the three climate trends presented in this paper. The values shown for each climate trend are averages of all four scenarios simulated for each trend.

The projected change in precipitation especially during spring and summer modifies the amount of soil water available to plant transpiration during the vegetation period from March to October. To show the changes in plant available soil water (PASW), the average of the actual plant available water is divided by the plant available field capacity (PAFC; the amount of soil water stored between permanent wilting point and field capacity) for each 1km grid point. On average, 63% of this potentially plant available soil water is accessible to plants during the vegetation periods of the past (Fig. 4). Due to the diminishing summerly precipitation and the increasing evapotranspiration because of higher air temperatures, the PASW during the vegetation period has a negative trend in all GLOWA-Danube scenarios. The average PASW for the second half of the scenario period is therefore reduced to 61% for *IPCC regional*, to about 58% for *REMO regional* and to only 54% for *Extrapolation* scenarios (Fig. 4). Overall, the results show a reduction of PASW during the vegetation periods of 2036 - 2060 by 3-15% when compared to 1971 - 2000.

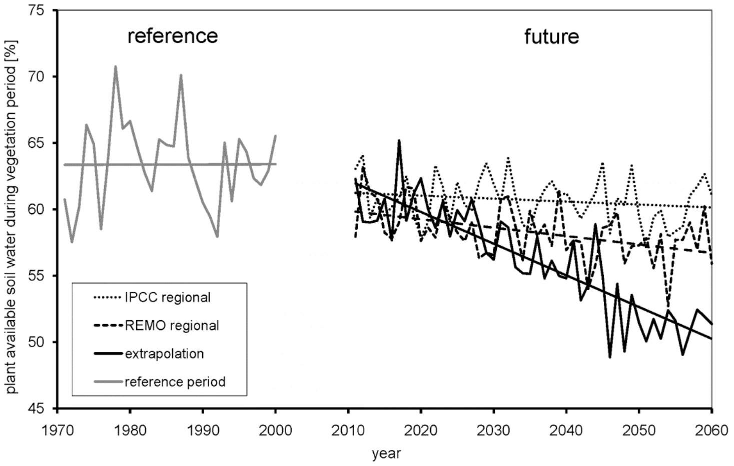

Fig. 4 Mean of the percentage of plant available soil water content during the vegetation period of each year for the reference period (1971 – 2000) and the three climate trends presented in this paper. The values shown for each climate trend are averages of all four scenarios simulated for each trend.

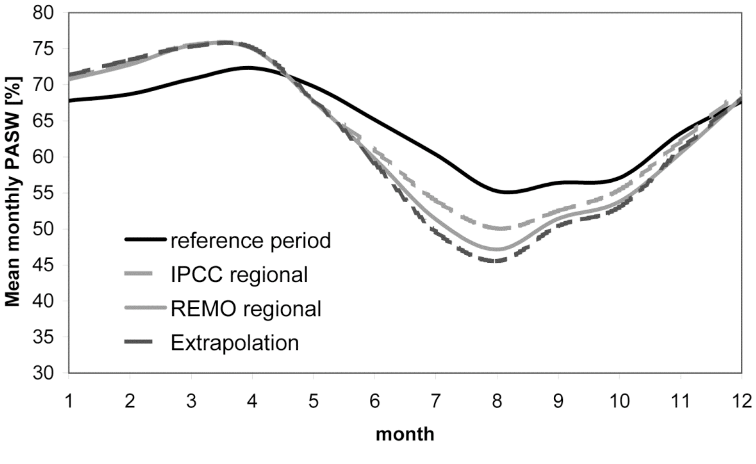

Fig. 5 Mean monthly plant available soil water computed for the reference period (1971 – 2000) and for the second half of the scenario period (2036 – 2060) with the three climate trends presented in this paper.

Further analysis of the temporal distribution of the PASW shows more distinct differences between wet months in winter and dry months in summer (Fig. 5). While the mean monthly PASW during the reference period only deviates between 55% and 70% of the potentially plant available field capacity, the winterly PASW in the second half of the scenario period averages to about 75% for all scenarios mainly because of higher temperatures and therefore less snow cover and more precipitation infiltrating into the soils of the catchment during winter. On the contrary, the higher evapotranspiration sums due to higher temperatures and the decrease in summerly precipitation lead to a more distinct minimum in PAFC fraction for the second half of the scenario period. As shown in Fig. 5, the main driver for this change is the higher evapotranspiration due to temperature increase compared to the differences in the change of precipitation for the three climate trends. On one hand, the scenario with the weakest decrease in summer precipitation (*IPCC regional*) has an average August minimum of 50% of the PAFC compared to 55% during the reference period. On the other, the climate trend with the much stronger decrease in summerly precipitation plus an even stronger increase in temperature (*Extrapolation*) has an August minimum of 45.5%. But as shown in Fig. 4, the strong negative trend in summer precipitation of the *Extrapolation* scenarios leads to a much stronger negative temporal trend in plant available soil moisture during the vegetation period than for the other scenarios.

Although soil water content in summer decreases during the scenario period, water availability for most of the plants that cover the Upper Danube region is still high. But mainly in the less humid central and northern parts of the catchment, the frequency of dry soil conditions increases.

Directly Linked to soil water availability is the percolation of water to the groundwater aquifers. In case soil moisture increases due to high precipitation, the percolation will also increase (if the demand of plants and soil evaporation are saturated) and vice versa.

As in most of the parts of the northern hemisphere, in the Upper Danube region the percolation of water to the saturated zone occurs mainly from November to March during the hydrological winter half-year, although the amount of precipitation in most of the parts of the Upper Danube region is the highest in the summer half year from May to October. This is due to the fact that evapotranpiration in the winter half year, because of lower temperature and reduced plant-growth, diminishes percolation less than during the growing season (Mai-October). In this context, a decline in percolation in the summer period, due to the expected climate change in the region, may have a strong impact on the availability and the quality of drinking water. In the Upper Danube region a significant decrease in precipitation in the summer period is expected (Tab. 1 and Mauser *et al.*, 2009) based on the climate trends used in this study. Furthermore, the predicted temperature rise will lead to an increase of evaporation as well as to an increased water demand of the vegetation.

In the reference period (1971-2000) the percolation in summer (June to August) has a fraction of approximately 29% of the total annual percolation (Fig. 6). The average annual percolation for the reference period amounts to 558 mm, whereas the minimum is 365 mm and the maximum is 794 mm.

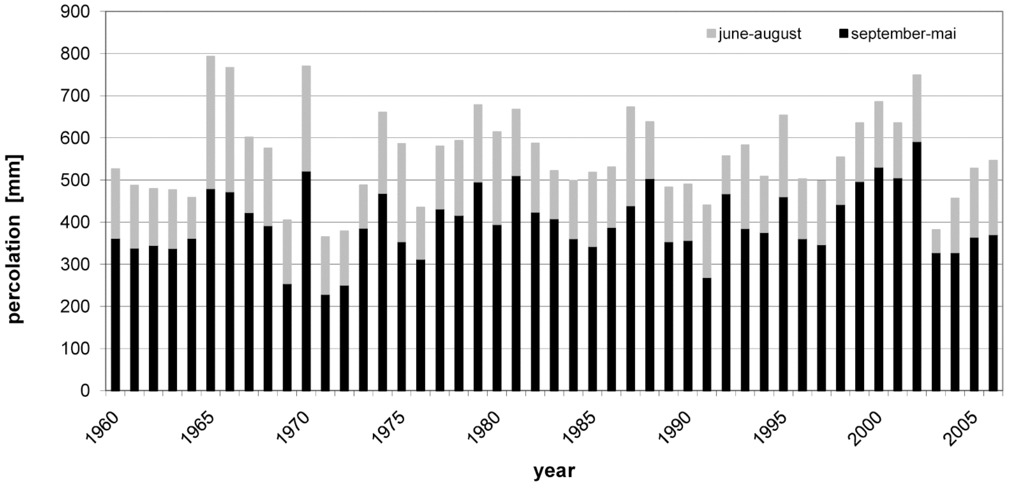

Fig. 6 Annual percolation during the extended reference period divided into the sum over the summer months (JJA) and the sum over September to May.

The results of the *REMO regional – Baseline* scenario show a clear reaction of the percolation to the changes in climatic conditions (Fig. 7). The percolation in summer is only 17% of the annual average, compared to 29% in the reference period. Moreover, the average annual percolation with 494 mm, the annual minimum with 328 mm as well as the annual maximum with 691 mm are clearly reduced, compared to the reference period. Furthermore, the annual percolation sum rarely exceeds 500 mm in the second half of the scenario period (2036-2060).

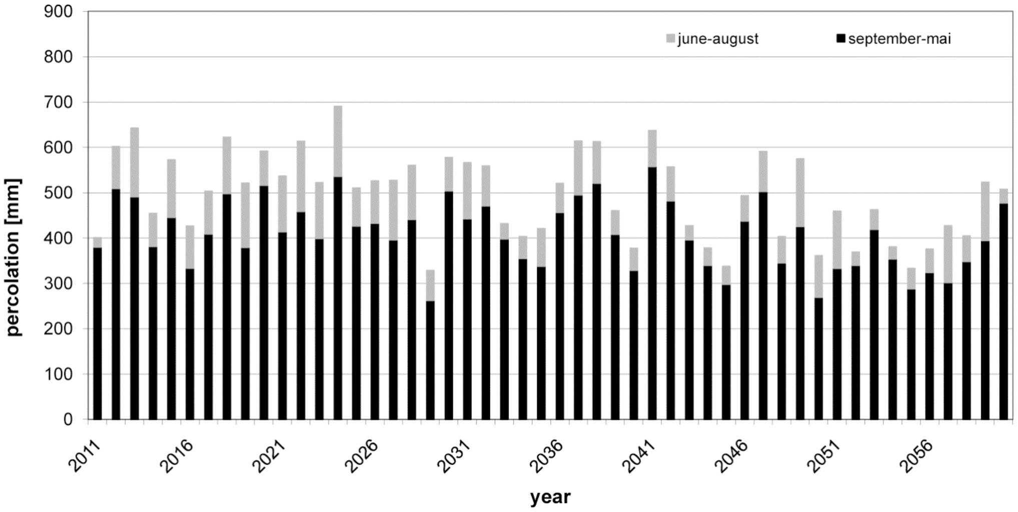

Fig. 7 Annual percolation of the *REMO regional – Baseline* scenario divided into the sum over the summer months (JJA) and the sum over September to May.

CONCLUSIONS

The potential impacts of future changes in the temporal distribution and the amount of precipitation, together with an increase in air temperature on root zone soil moisture are investigated. Future availability of soil water for plant transpiration and therefore biomass production is of great interest to agricultural and forestry planning. Furthermore, the described change in climate together with the adaptation of the plants to warmer temperatures and likely prolonged vegetation periods lead to the alteration of the water fluxes at the land surface, especially the recharge of groundwater from the soil root zone. Water fluxes at the land surface are described by a physically based model (PROMET), which includes a dynamical vegetation module and an explicit model of soil water fluxes amongst others.

It is shown that all members of the ensemble of GLOWA-Danube climate scenarios presented in this paper have a similar effect on the soil water dynamics of the land surface. During the reference period 1971-2000 on average two-thirds of the potential plant available soil water storage is accessible to plants from March to October. Similar to the slight to moderate decrease in annual precipitation in most scenarios, this storage is reduced by 3-15% during the investigated scenario period 2036 to 2060. Likewise, the annual mean root zone percolation is reduced by 7-14% when comparing these two periods. However, a stronger decrease in summer precipitation together with higher air temperatures will have a more drastic effect on soil water during summer. Summerly groundwater recharge is estimated to decrease by 24-59% and because of decreased average soil moisture content during the second half of the scenario period, droughts in the central and northern region of the basin may likely occur more often.

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